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ATOMIZING MOLTEN METALS - A REVIEW

by

C. F. Dixon

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PHYSICAL METALLURGY DIVISION

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C. F. Dixon*

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SYNOPSIS

Different processes for producing atomized metal powders are described and factors that effect the shape and size of powder particles are discussed.

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ATOMIZING MOLTEN METALS - A REVIEW

1. INTRODUCTION

The production of metal and alloy powders has been an important industrial activity for many years. There are many routes which may be used to yield finely divided metallic particles ranging from mechanical comminution, through chemical reduction of pulverized brittle compounds, and chemical and electrolytic reduction from solution, to the physical disintegration of liquid metal. This review is concerned only with the latter.

~~Differing from massive metal, in ingot, casting or wrought form,~~ metal powders may ~~have~~ contain particles and diameters between 150 microns (100 mesh) and a fraction of a micron. ~~Metal powders~~ and such powders may be described as coarse, fine, and ultra-fine within such a size range, ~~although commercial moulding grade powders normally are between 150 and 44 microns (100 and 325 mesh) in diameter.~~ 80% ~~Bearing this in mind, it is evident that~~ particles coarser than 100 mesh are not powder material in the accepted sense and ~~certainly~~ are not usually of application ~~to~~ in conventional powder metallurgy ~~applications such as die moulding, pressing and sintering~~ production technology.

The physical disintegration of liquid metals (depending on the particular technique employed) can be described as granulation or shotting if relatively coarse particles result and as atomization if a fine powder is produced. Because even the ultra-fine particles, less than 1 micron in diameter, are composed of millions of atoms, it is evident that "atomization" is strictly inaccurate; however, it has become the generally accepted term, popularly and industrially, to describe the creation of fine particles below 150 microns in mean diameter. The current definition of atomization used industrially (ASTM, MPIF, ASM) simply terms it the dispersion of a molten metal into particles by means of a rapidly moving stream of gas or liquid. In this method, a gas or liquid impinges on and shears a molten metal stream to form ligaments or threads which break up into fragments and droplets. The shape and size of these, which form powder particles on cooling, depend on a number of process variables.

Theoretically, the rapidly moving gas or liquid could move in any direction relative to the molten metal provided that there is an impingement of one with the other. In practice, it is unusual for a stream of molten metal to be surrounded by a high-velocity jet of gas or liquid, the metal being atomized in either a vertically downwards or horizontal direction. A comprehensive study of atomizing liquids

is covered by R. P. Fraser et al [1] and W. D. Jones [2]; and the mechanism of atomizing molten metal by a gas jet is discussed by Putimtsev [3] and Naida [4].

In the development of modern atomizing techniques, there are processes that do not utilize rapidly moving streams of liquids or gases. However, all "atomizing" processes ~~disperse~~ convert molten metal into powder and, in this review, this broader definition of atomizing will be used.

Most metal powders can be produced by atomization. Because of the high purity of powders atomized in inert atmospheres and the ~~finely divided~~ fine grained homogeneous structure in subsequently the fabricated material, this process has technical attractions attention is drawn to this process for the production of pre-alloyed iron-base alloy powders for forging of preforms and for the production of high-temperature alloy powders such as stainless steels ~~and~~ the cobalt- and nickel-base superalloys.

Much progress in atomizing metal powders has been made by industry and although detailed the information is considered proprietary there is a considerable amount of available published material which is the basis of this review.

2. ATOMIZING PROCESSES

2.1 Ferrous Metals

Though the production of metal powders by atomization is not a new concept, large-scale production of powder by this method did not occur until the Second World War. A shortage of copper powder in Germany led to the development of methods for making driving bands for shells from iron powder, so two processes, the D.P.G. and Mannesmann (RZ) were developed to produce atomized iron powder. After the war, a demand for atomized powder, mainly stainless steel, resulted in the development of other atomizing processes in the United States and Great Britain.

2.1.1. D.P.G.

In the D.P.G. process, molten metal flows from a hole in the bottom of a heated tundish through an 8 to 10-mm (0.3 to 0.4-in.)-diameter alumina nozzle, through the apex of a cone-shaped jet of water, and onto stainless steel knives mounted on a rapidly rotating disc (Figure 1). The powder is cooled in a reservoir of water. Water-jet pressures in the order of 0.4 MN/m^2 (60 psi) are used and the speed of rotation of the disc is between 1500 and 3500 rpm.

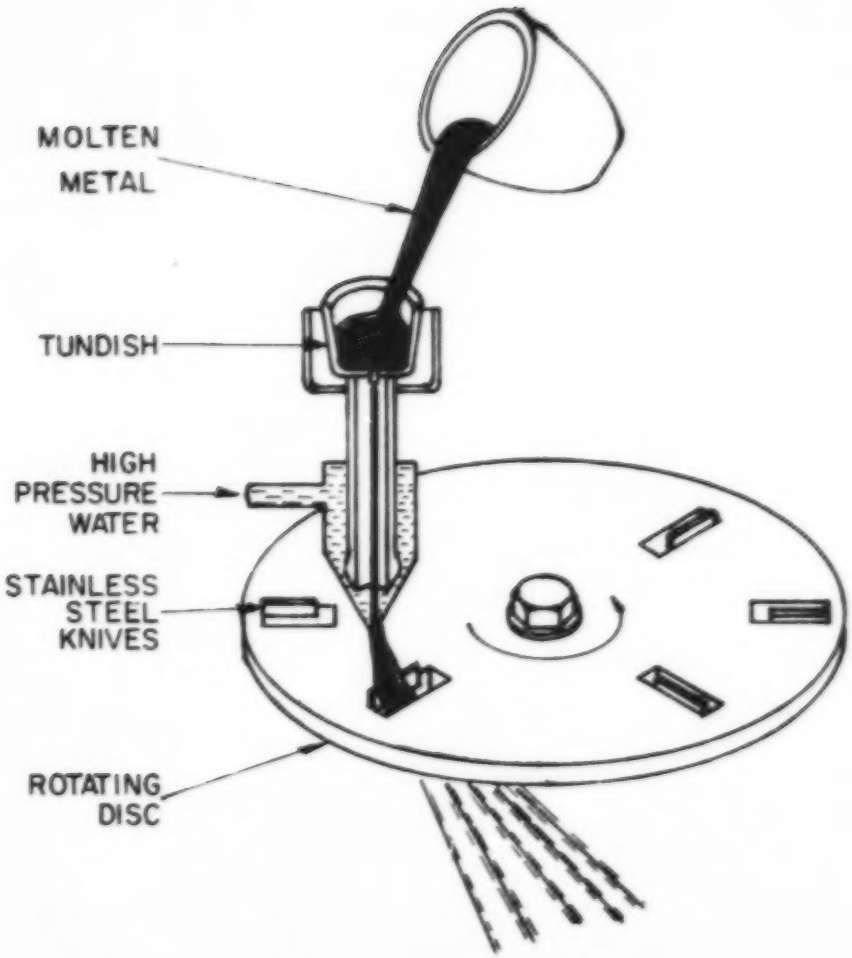


FIGURE 1. D.P.G. Process.

The D.P.G. process gave operating difficulties inherent to equipment rotating at high speeds; the metal froze on the knives, and the powder was oxidized and too coarse. This process appears to have not been used since the war.

2.1.2. Mannesmann

The Mannesmann process uses an annular jet of air to atomize a molten stream of high-carbon iron. Figure 2 is a diagrammatic sketch of the atomizing unit. During atomization, oxidation takes place and carbon monoxide is formed within the liquid metal causing the droplets to form hollow spheres which fall into a water bath. The powder is dried and then heated at 950°C (1740°F) and, if the carbon:oxygen ratio (1.5:1) is correctly controlled, a reaction between the oxygen and carbon proceeds to completion to leave a deoxidized, decarburized, and sintered cake. The cake is broken down by ball milling to a high-quality pure-iron powder.

Under normal operating conditions, a metal flow of 0.6 kg/sec (83 lb/min) is employed. An air pressure of 0.7 MN/m^2 (100 psi) is used and the width of the annular air slit is 3 mm (0.1 in.).

A number of variables such as carbon content of melt, conditions of atomization, and treatment after atomization have

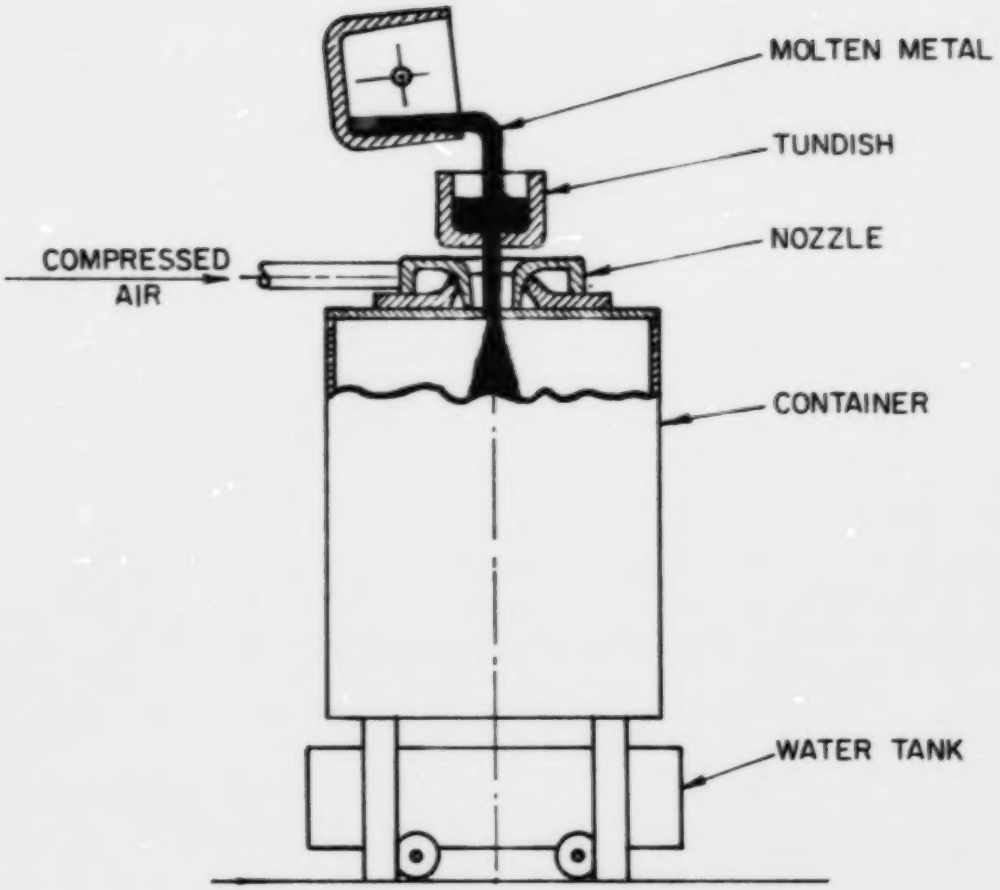


Figure 2. Mannesmann Process (RZ).

to be controlled. However, this process was considered to be more economical than the D.P.G. process and several modern plants are using modifications of the RZ process to produce ferrous powders commercially.

2.1.3 Rotating Water-Jet

A rotating water-jet process used by the Vanadium-Alloys Steel Corporation to produce stainless steel powders [5,6] is illustrated in Figure 3 [7]. In this process, a stream of molten metal flows from the bottom of a zirconium-silicate-lined tundish through a 5 to 11-mm (0.2 to 0.4-in.)-diameter zirconia nozzle and is atomized by jets of water issuing from holes on the periphery of a rapidly rotating disc. The yield of fine powder(minus 150 microns,100 mesh) is reported to be in the order of 40%.

2.1.4 Annular Jet

W. D. Jones [8] describes a process used by Powder Metallurgy Limited of Great Britain to produce ferrous alloy powders. A stream of molten metal, less than 10 mm (0.4 in.) in diameter, flows down through a hole in the bottom of a tundish and is atomized by passing through the apex of a high-velocity conical stream of water emerging from an annular nozzle ,

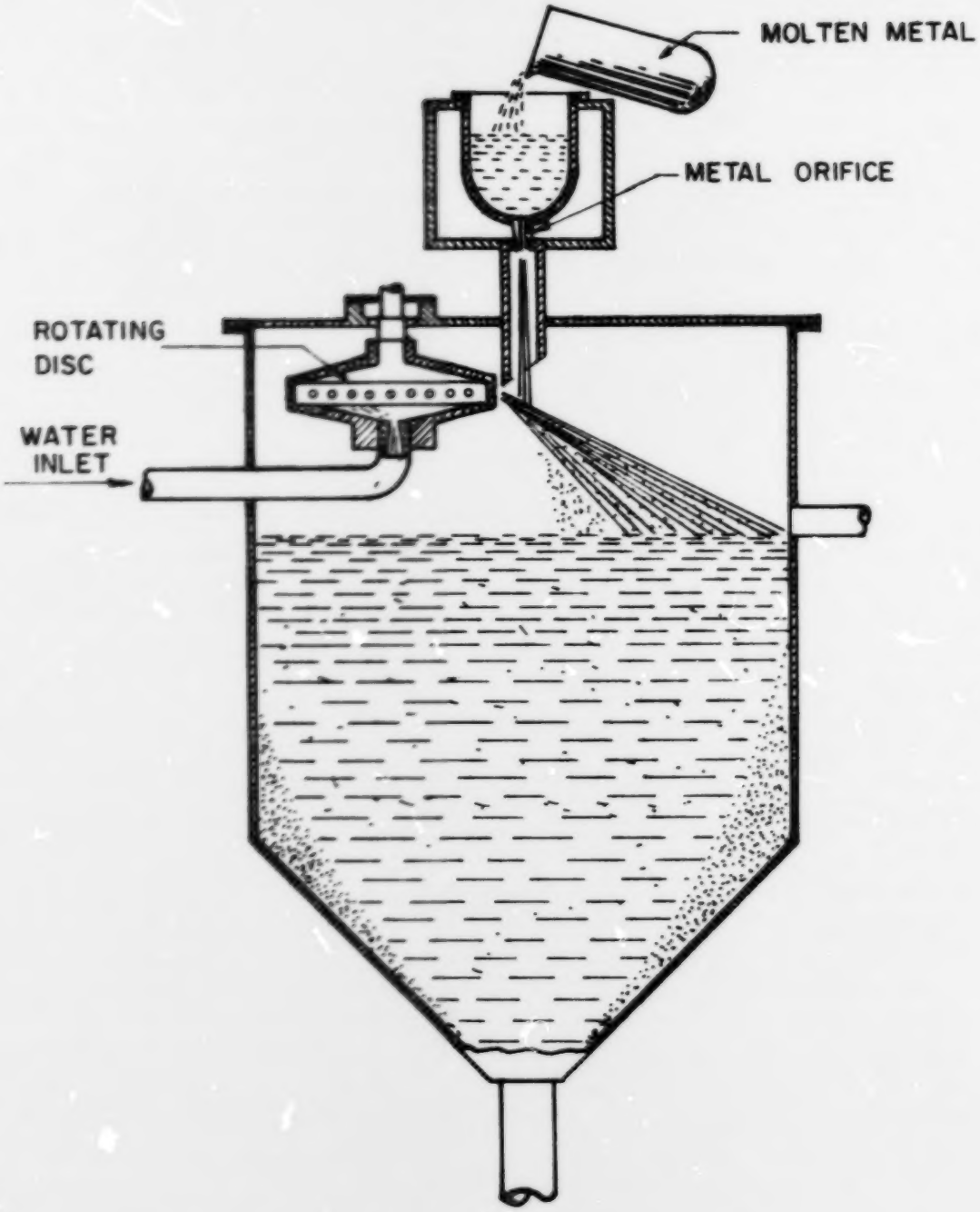


Figure 3. Rotating Water-Jet Process.

19 to 25 mm (0.8 to 1 in.) in diameter. Water velocities of 90 to 150 M (300 to 500 ft)/sec and pressures of 14 to 20.5 MN/m^2 (2000 to 3000 psi) are used and the production of 100% minus 65-micron (240-mesh) powder is possible. A schematic drawing is shown in Figure 4. This type of apparatus is also described in British Patent (B.P.) 553,672 [9].

Watkinson [10] discusses the use of an apparatus of the above design by the BSA Co. Ltd., Great Britain, to produce nickel-base high-temperature alloy powders and stainless steel powders. To overcome the problem of oxidation, the powders are atomized into an inert atmosphere. By this method, the oxygen content of low-silicon stainless steel powders was reduced from 6% to less than 0.5%.

A problem with this process is that there is always a small reservoir of molten metal at the apex of the jet, and, if the metal is fed too rapidly, this reservoir fills up into the jet body and blocks it. Also, some low-fluidity alloys give wavering streams which catch the side of the nozzle and freeze, and cause blockage.

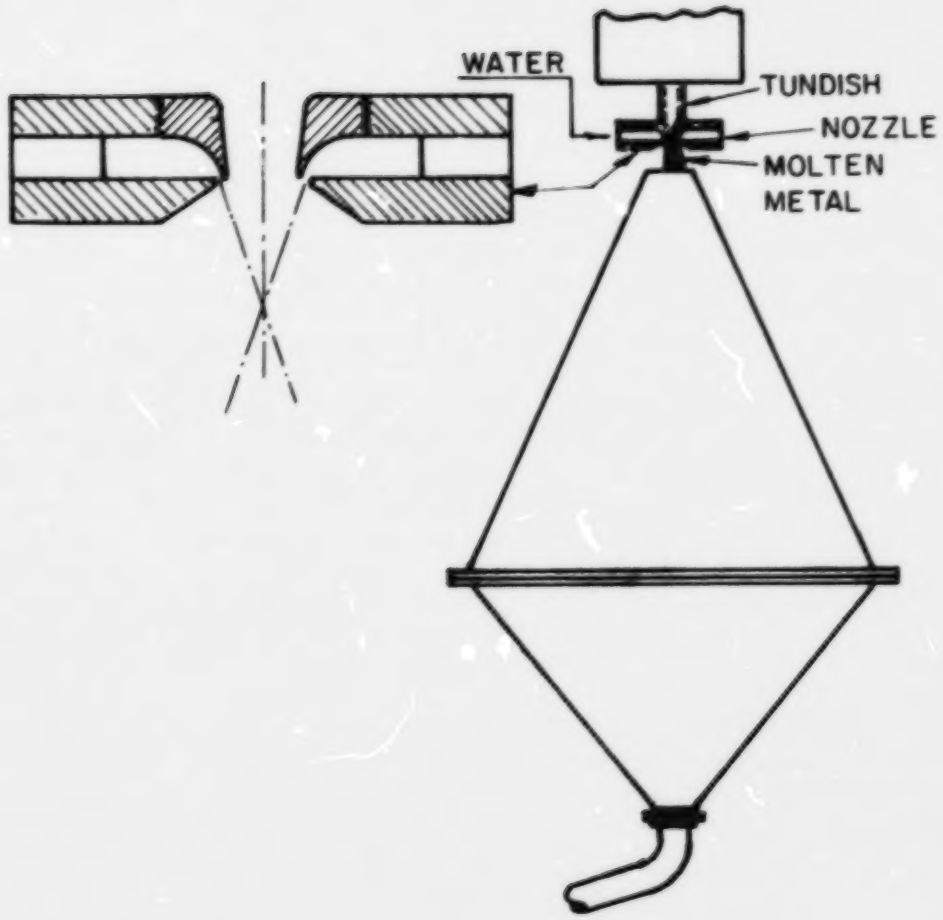


FIGURE 4. Annular Jet (Water).

2.1.5 V-Jet

To overcome the problems associated with the annular nozzle, a V-jet nozzle was developed in Sweden by Hoeganaes. In this process, molten metal is fed into a trough formed by the intersection of two flat streams of water. A recent paper by Gummeson [11] discusses different arrangements of V-jets, from simple flat stream jets shown in Figure 5 to the intersecting - and multiple-jet configurations shown in Figure 6. Gummeson also lists the major variables in the atomizing process (Figure 7) and quotes an example of operating conditions for a V-jet system as:

Metal temperature	1510°C (2750°F) ,
Metal nozzle diam.	7 mm (0.3 in.) ,
Metal flow rate	22 kg (48 lb)/min ,
Jet apex angle	100 deg ,
Water pressure	9 MN/m^2 (1300 psi),
Water flow rate	34 ℓ/s (44 gal/min),
Water velocity	113 m (370 ft)/sec , and
Powder yield	38% minus 147 microns (100 mesh)

Important features in the design of V-jets are: length of metal stream, length of jet, and size of apex angle of the jet. Short stream and short jet permit more efficient energy

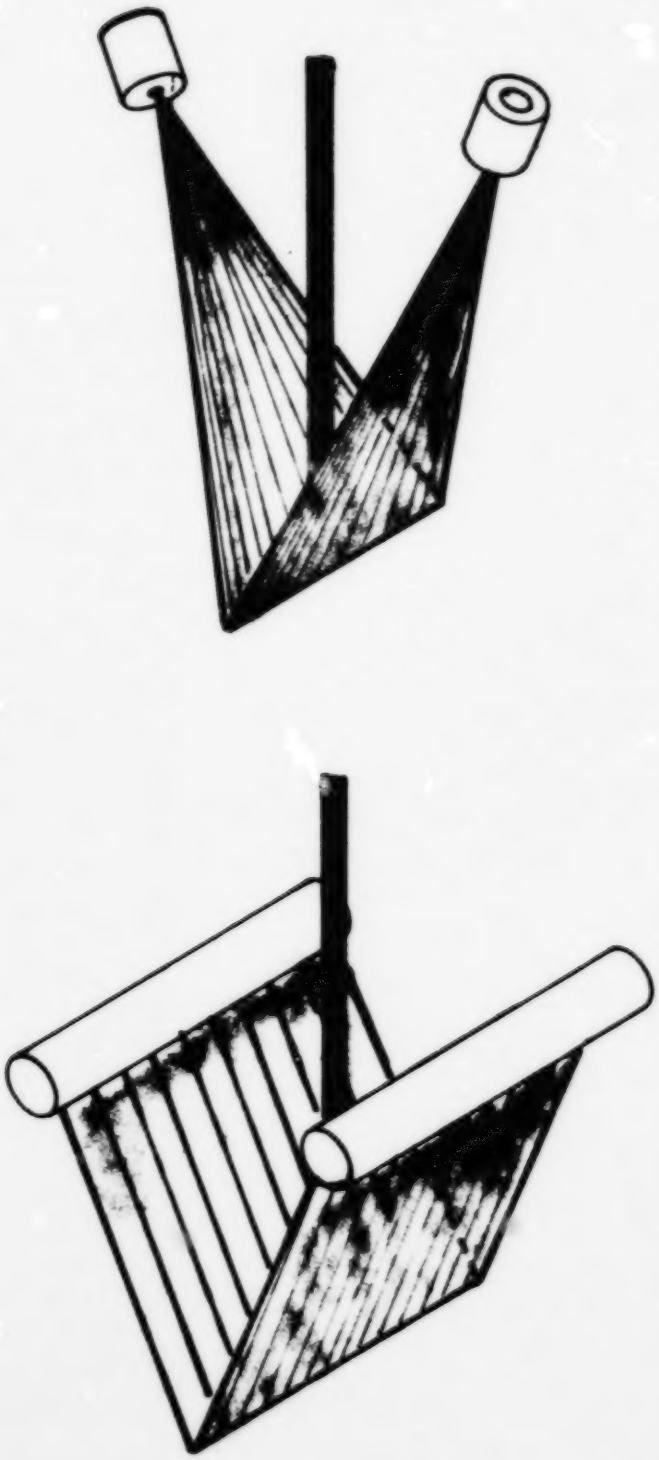


Figure 5. Simple V-Jets.

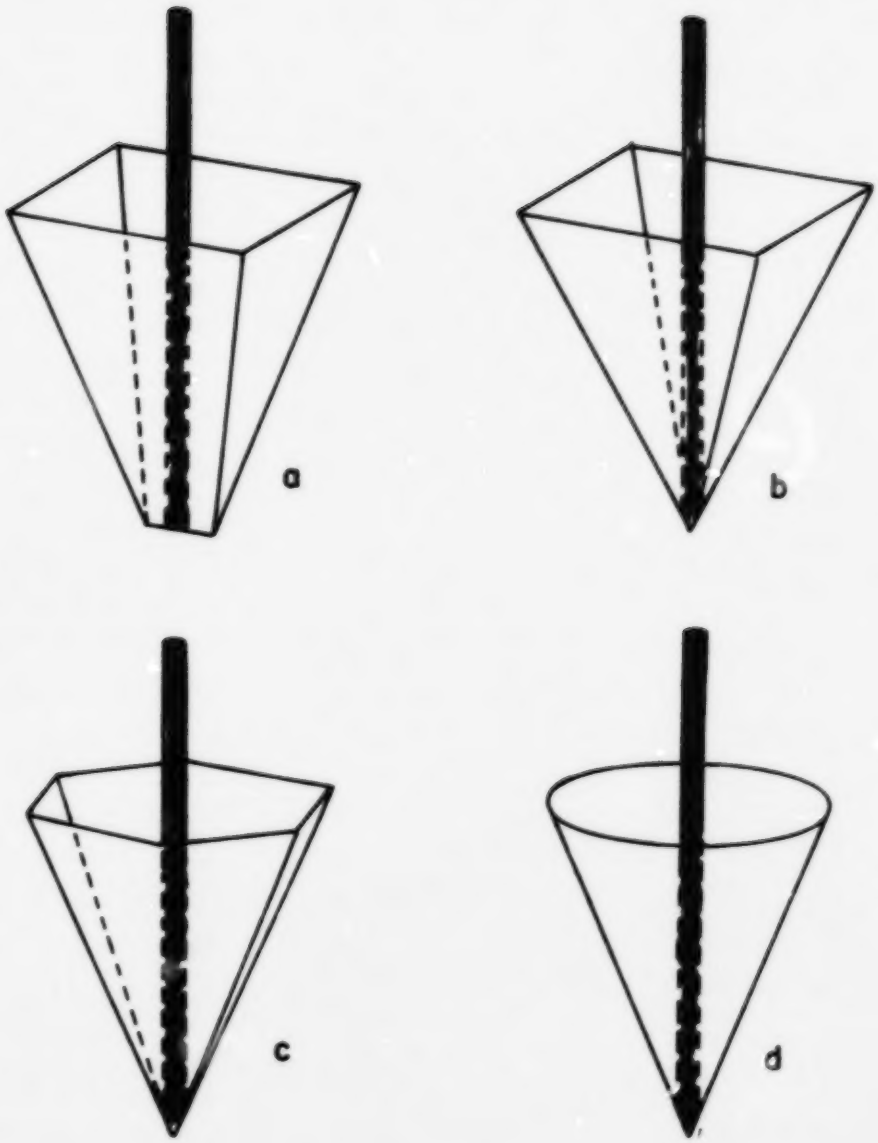
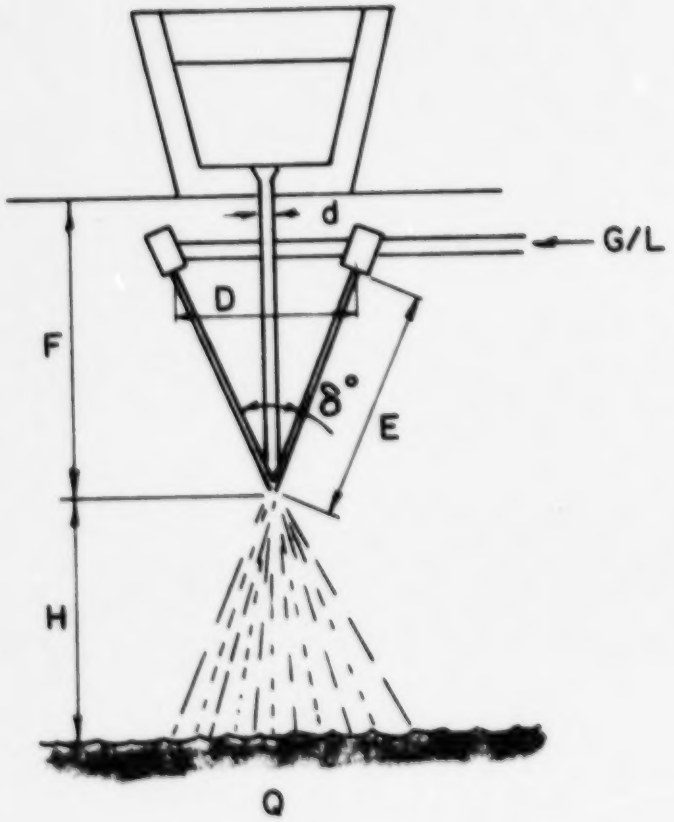


Figure 6. V-Jet Configurations.



ATMOSPHERE: During melting
In Atomizing Tank

MOLTEN METAL: Chemistry
Viscosity
Surface Tension
Temperature Range
Superheat
Feed Rate
Nozzle Diameter (d)

ATOMIZING AGENT: Gas or Liquid (G/L)
Pressure
Flow
Velocity
Viscosity

JET GEOMETRY: Spread (D)
Length (E)
Metal Stream Length (F)
Jet Apex Angle ( )

TANK PARAMETERS: Flight Path (H)
Quenching Medium (Q)

Figure 7. Process Variables For V-Jet Atomization.

utilization and finer powder. The proper jet angle, which must be established experimentally for each system, will be discussed later.

To obtain reasonably fine powder, the metal orifice diameter is usually under 13 mm (0.5 in.).

Oxidation of water-atomized powders using V-jets can be reduced by introducing inert or reducing gas in the region of atomization and by maintaining the water level in the tank close to the nozzle assembly; this minimizes hot exposure and hastens quenching of the metal powder.

2.2 Metals That Have a Low Tolerance for Oxygen

Modern demands for high-performance materials, capable of operating under severe conditions at elevated temperatures, have resulted in the application of atomizing techniques to the production of the nickel-base superalloys. Rigid specifications on purity and on oxygen content rule out atomizing with either air or water and a new generation of processes has been developed based on atomizing either in a vacuum or in an inert atmosphere.

According to Bufferd and Gummeson [12], three types of processes are being used commercially to atomize the superalloys; inert-gas, rotating-electrode, and soluble-gas atomization. Atomization by rotating-vane, ultrasonic, and "metallization" (wire electrodes are melted by an electric arc formed between them) processes are also mentioned in the literature.

Other powders that have low tolerance for oxygen and are produced by inert-atmosphere atomizing techniques are high-speed tool steel powders and heat-treatable ferrous-alloy powders (containing reactive elements such as chromium and manganese) for the forging of preforms.

2.2.1 Inert Gas

The inert-gas atomization process disperses a stream of molten metal by means of a jet of rapidly moving inert gas. The powder size distribution is usually broad, with 10 to 25% minus 44 microns (325 mesh). Control of particle size is possible by varying the design of the atomizing nozzle, the gas pressure, and the size of metal stream. This process is used by Stora Kopparberg in Sweden [13].

With external annular gas jets, there is a problem with the cone of rapidly moving gas ejecting the atmosphere from the

area within the cone, to form a vacuum or dead spot. The atomized metal collects in this area, adheres to the nozzle, freezes,and prevents further atomization. It is also difficult to obtain equal distribution of pressure around the annular jet . Several Russian investigators have examined these problems.

Silaev and Rokovskii [14] claim that a vacuum can be prevented from forming inside the gas cone by: partitioning the annular jet gap as shown in Figure 8(a); using a series of cylindrical orifices as shown in Figure 8(b); and by feeding gas through a channel into the cone.

Lev et al [15] examine the use of ducts through which some of the compressed gas can pass to equalize the pressure inside the cone. A nozzle of this design is shown in Figure 9. Because the metal stream is in contact with the nozzle, erosion of the nozzle would be expected.

Naida and Nichiporenko [16,17] discuss nozzle designs that will prevent metal freezing on the nozzle and also provide even gas pressure around the annular jet opening. The nozzle shown in Figure 10 has two air chambers which are connected by fifty 3-mm(0.1-in.)-diameter openings. Air is fed through two tangentially arranged pipes into the first chamber, passes through the second chamber and emerges into the atomizing zone

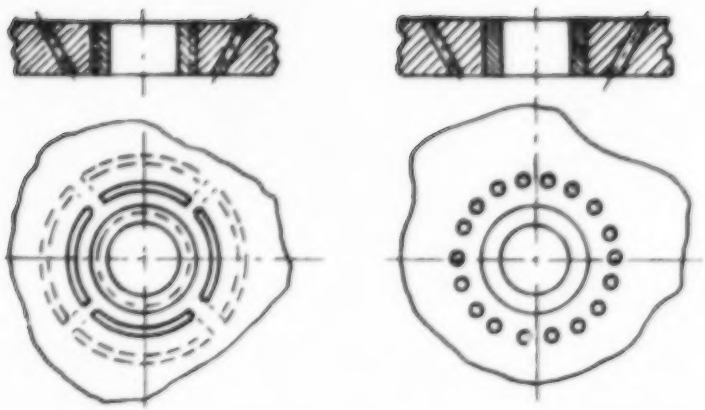


Figure 8. Annular Nozzles (a) Partitioned Annular Gap (b) Cylinderical Orifices.

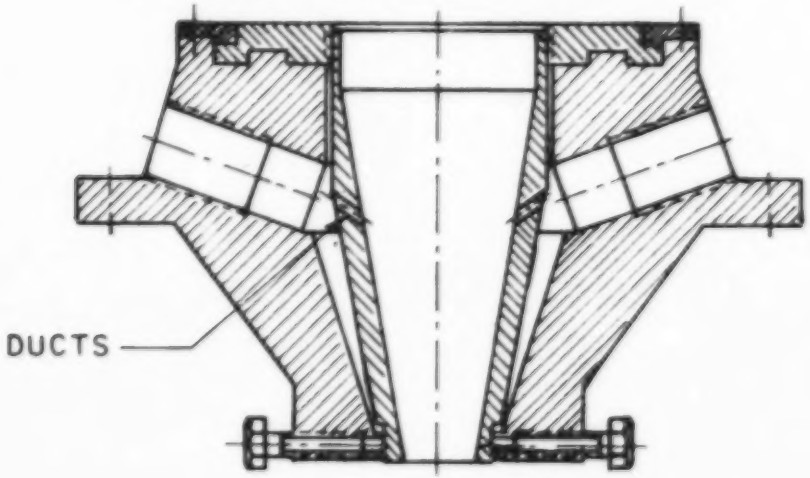


Figure 9. Annular Nozzle with Ducts that Allow Gas to Pass into Cone.

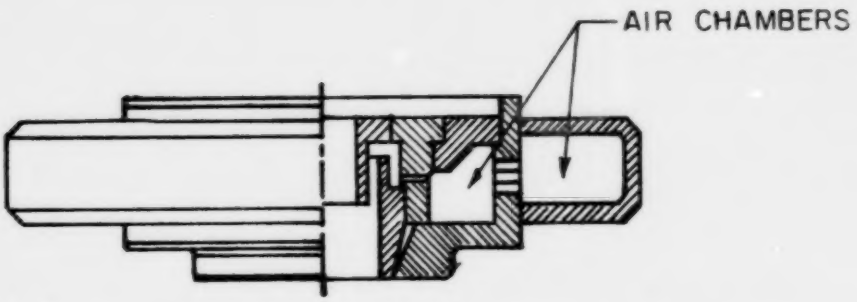


Figure 10. Gas Nozzle by Naida and Nichiporenko.

through an annular gap. A stable and uniform gas flow around the complete perimeter of the annular aperture is claimed. Also, 2 to 3-mm (0.08 to 0.1-in.) openings connect the gas chambers with the atomizing zone to equalize the pressure in the cone. This nozzle is reported to give good performance over a long period of time.

The production of nickel-base superalloy powder using V-jets of nitrogen and argon has been investigated by Ingram and Durdaller [18].

2.2.2 Rotating Electrode

In the rotating-electrode process, the metal is converted to powder by progressively melting the end of a rotating rod with an arc or plasma. Molten metal drops are thrown off by centrifugal force and collected in a gas-filled chamber. This process, described by Freidman and Kosinski [19], by Abkowitz [20], and in U.S. Patent (U.S.P.) 3,099,041 [21] is illustrated in Figure 11. The particle size distribution in the powder is narrow and is controlled by the speed of rotation of the rod. Powder composition, purity, and homogeneity depend on the rod composition. This process is being used by Whittaker Nuclear Metals to produce superalloy, Zircaloy-2, titanium

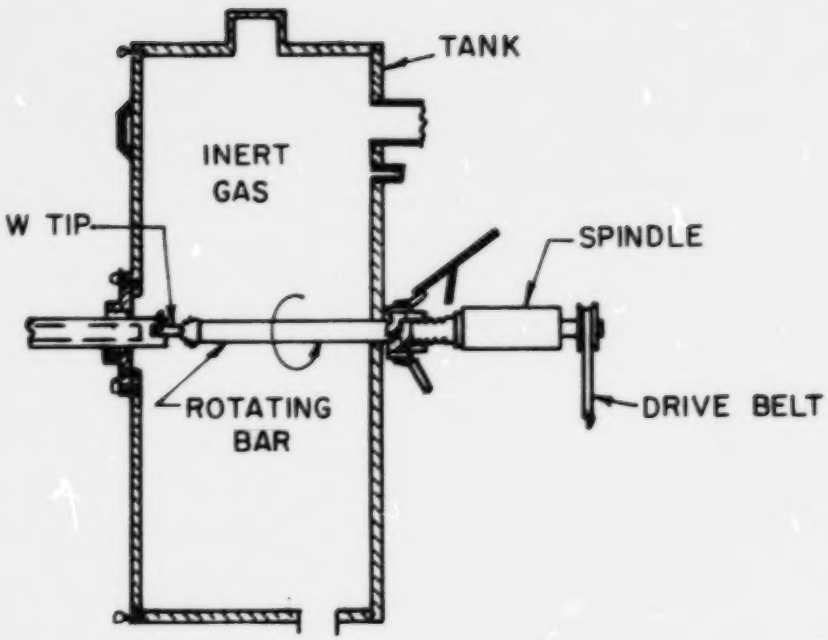


Figure 11. Rotating-Electrode Process.

titanium-alloy, and beryllium powders.

2.2.3 Soluble Gas

To produce powder by the soluble-gas atomizing process, molten metal is pressurized with a highly soluble gas such as hydrogen. The molten metal then passes through an orifice into a vacuum chamber where the pressurized liquid explodes into particles. A soluble-gas atomizing unit is illustrated in Figure 12 [22]. Particle size distribution tends to be coarse.

2.2.4 Rotating Vane

In a recently developed process, powder is produced by melting a metal rod with an electron beam. Falling drops of molten metal are hit by a rotating vane which disperses the drops into fine particles (Figure 13) [23]. The particles are basically spherical and about 45% minus 125 microns (120 mesh). This method has been used to produce only small batches of powder in laboratory-scale operations.

2.2.5 Ultrasonic

Spherical powders with a narrow size distribution can be produced by ultrasonic atomization. A schematic drawing is shown in Figure 14 [24]. In this process, molten metal is atomized by ultrasonic vibrations and allowed to solidify in an

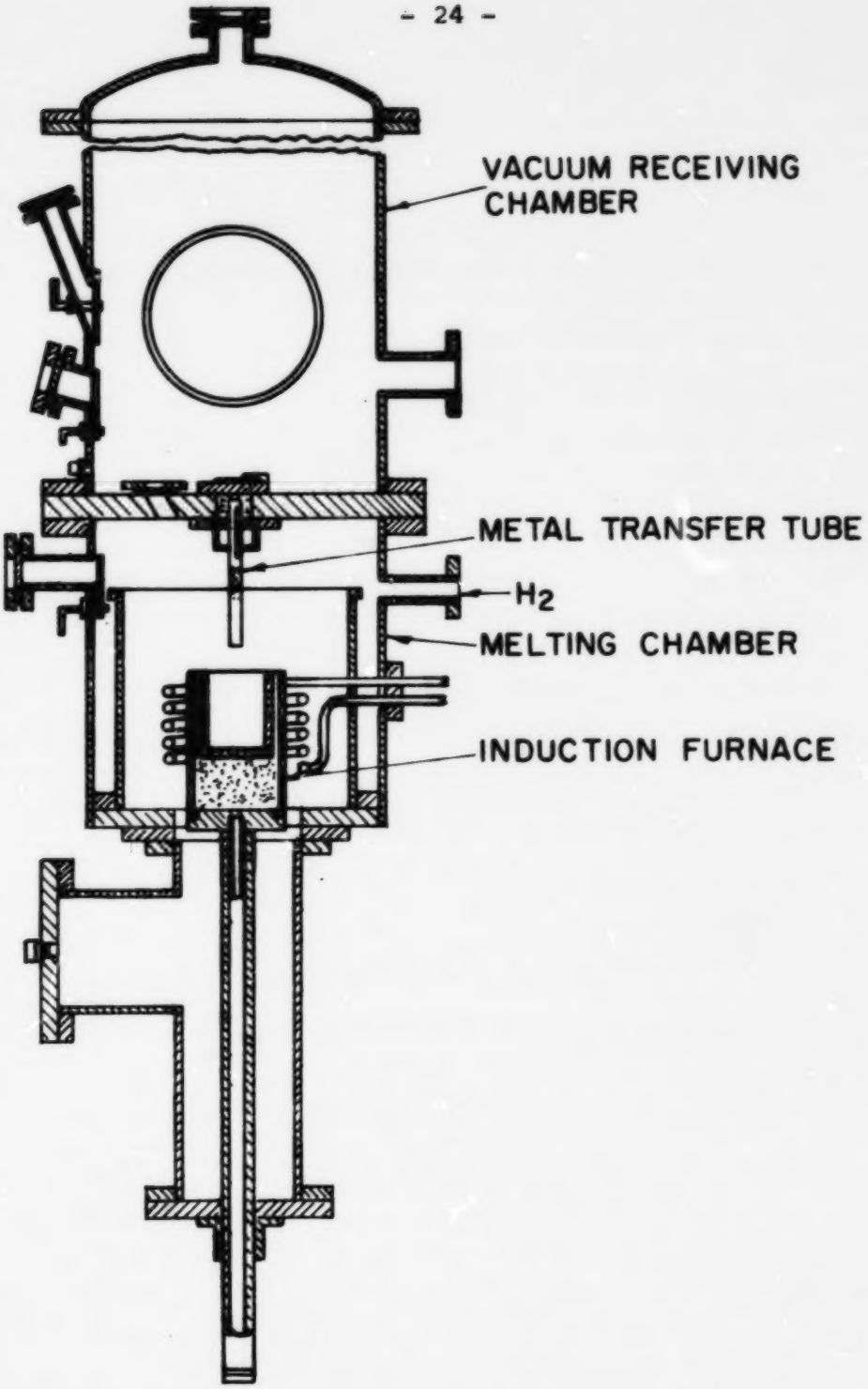


Figure 12. Soluble Gas Process.

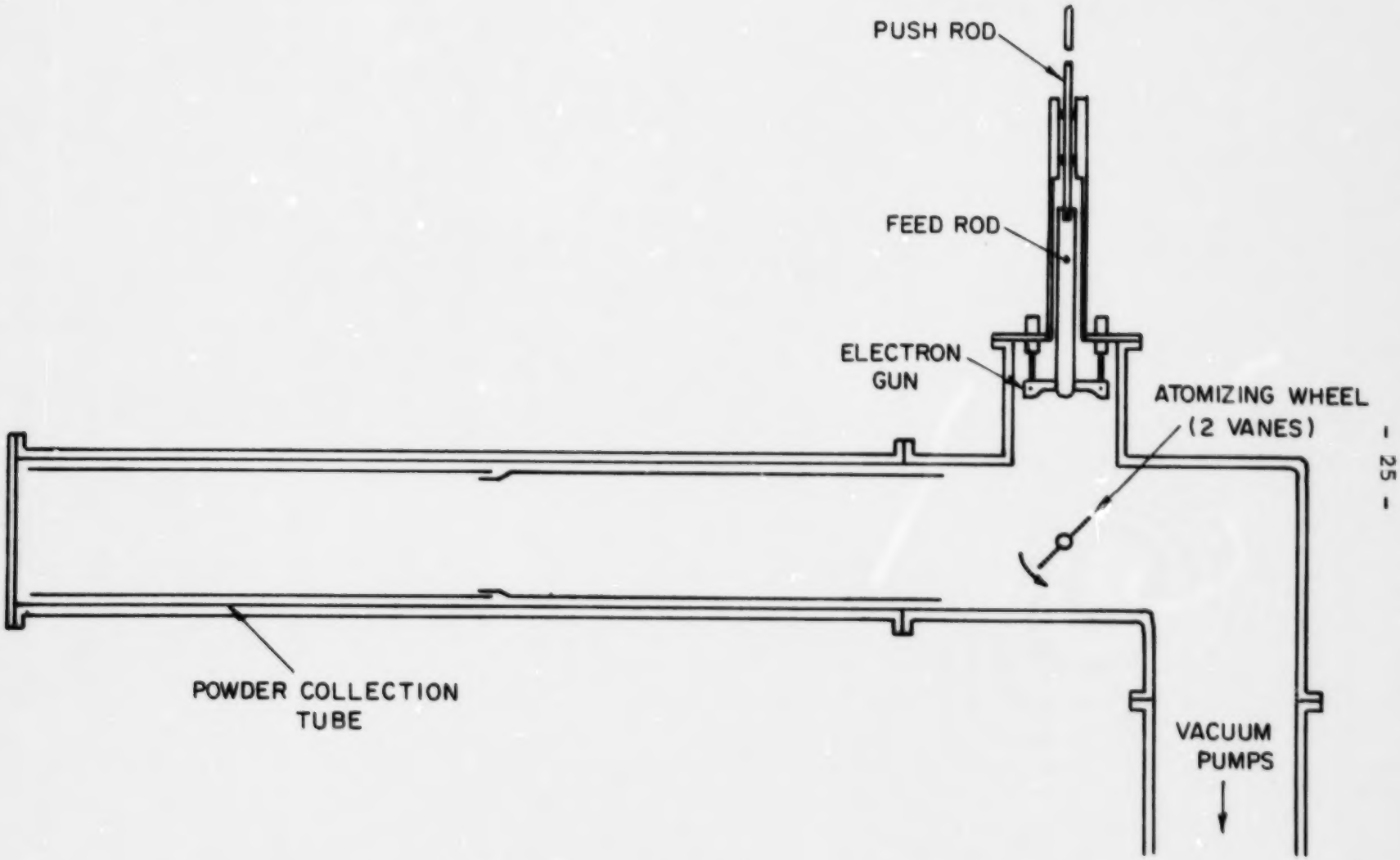


Figure 13. Rotating-Vane Process.

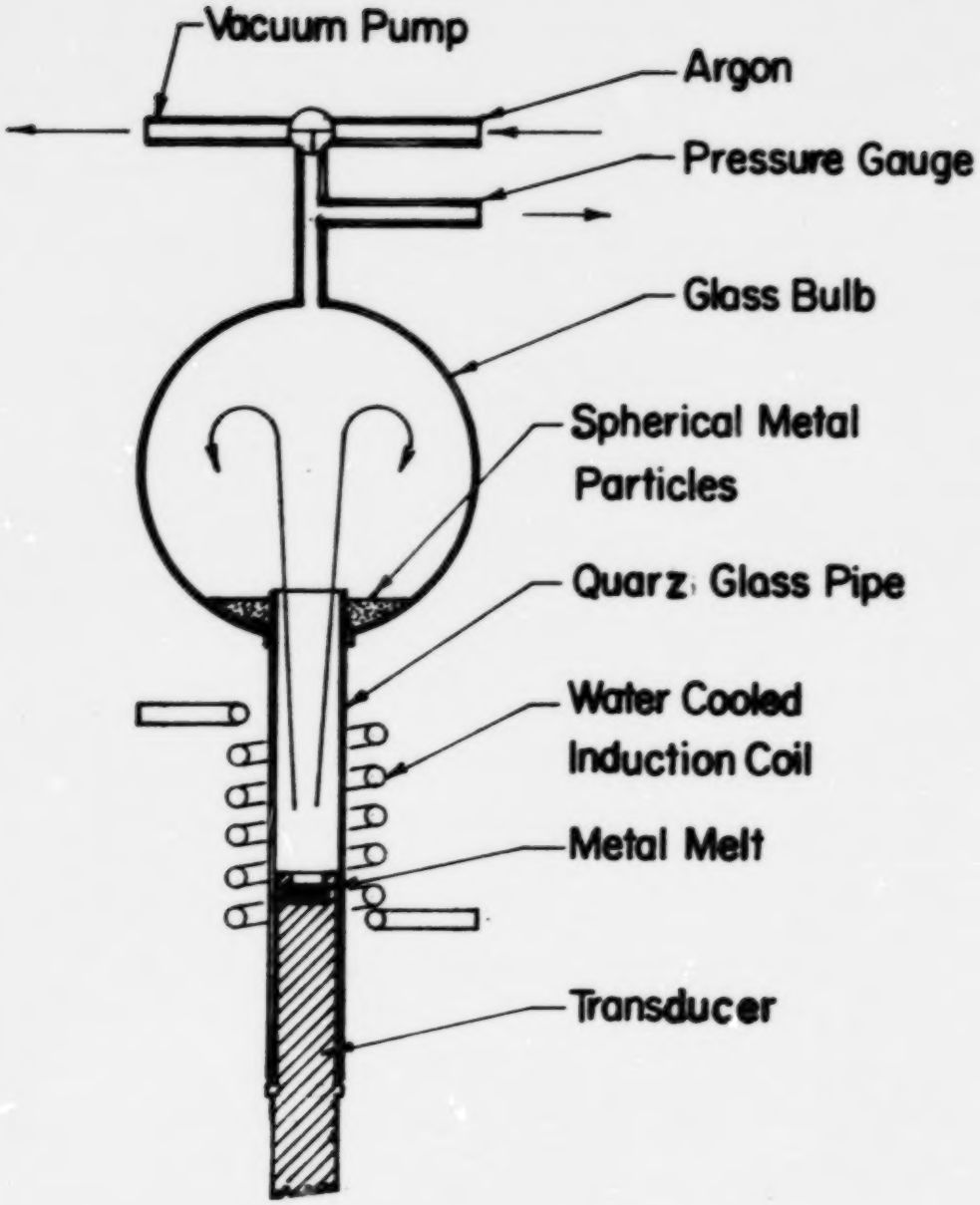


Figure 14. Ultrasonic Atomization Apparatus.

inert atmosphere. The powder size can be pre-selected by the frequency of oscillation. This apparatus is particularly suited to atomizing easily oxidized metals, but only those with melting points up to 700°C (1290°F) have been atomized.

2.2.6 Metallization

Pavlovskaya et al [25] describe the production of spherical and sphere-like powder from wire by means of electrometallization. Two-wire electrodes are fused by an electric arc formed between them,and the fused metal is atomized by a jet of compressed air. The powder particles are quenched in a water bath. Nickel and iron powders have been atomized.

The size of the powder can be decreased by decreasing the size of the wire and by increasing the air pressure. Composition of the wire also has an effect on powder size; under the same conditions of atomization, nickel powder is much finer than iron powder. Productivity increases with diameter of wire and rate of feed.

2.3 Non-Ferrous Metals

Most of the progress in the atomization of metal powders appears to be in the production of ferrous metals and the superalloys; there is little information available on the atomization

of non-ferrous powders. Gummeson [11] suggests that present commercial atomization of many low-melting-point alloys is done on apparati similar in design to those patented between 1915 and 1925. Examples are devices developed by Hall [26-28], and a nozzle for one of these is shown in Figure 15. This nozzle, like many in the earlier designed apparatus, is of the spray type and lifts the molten metal from a tank, through a conduit, to be atomized by an annular jet of gas or liquid issuing from the nozzle and converging on the metal stream. The heat of the molten metal is sufficient to keep the nozzle at operating temperatures.

In other earlier designs the molten metal is fed to the nozzle by gravity [29], or the nozzle is attached to the side of a crucible as shown in Figure 16 [30], or to the bottom of a crucible as in Figure 17 [31].

An apparatus previously described (Figure 4) was used by Powder Metallurgy Limited to produce non-ferrous powders, and F. W. Berk and Co. Ltd. has a patent [32] for using hydrocarbon oils in this apparatus to atomize reactive metals such as magnesium. In 1948, Thompson [33] published a paper on the effect of certain variables in air-atomizing aluminum with a spray-type nozzle. Figure 18 is a schematic drawing

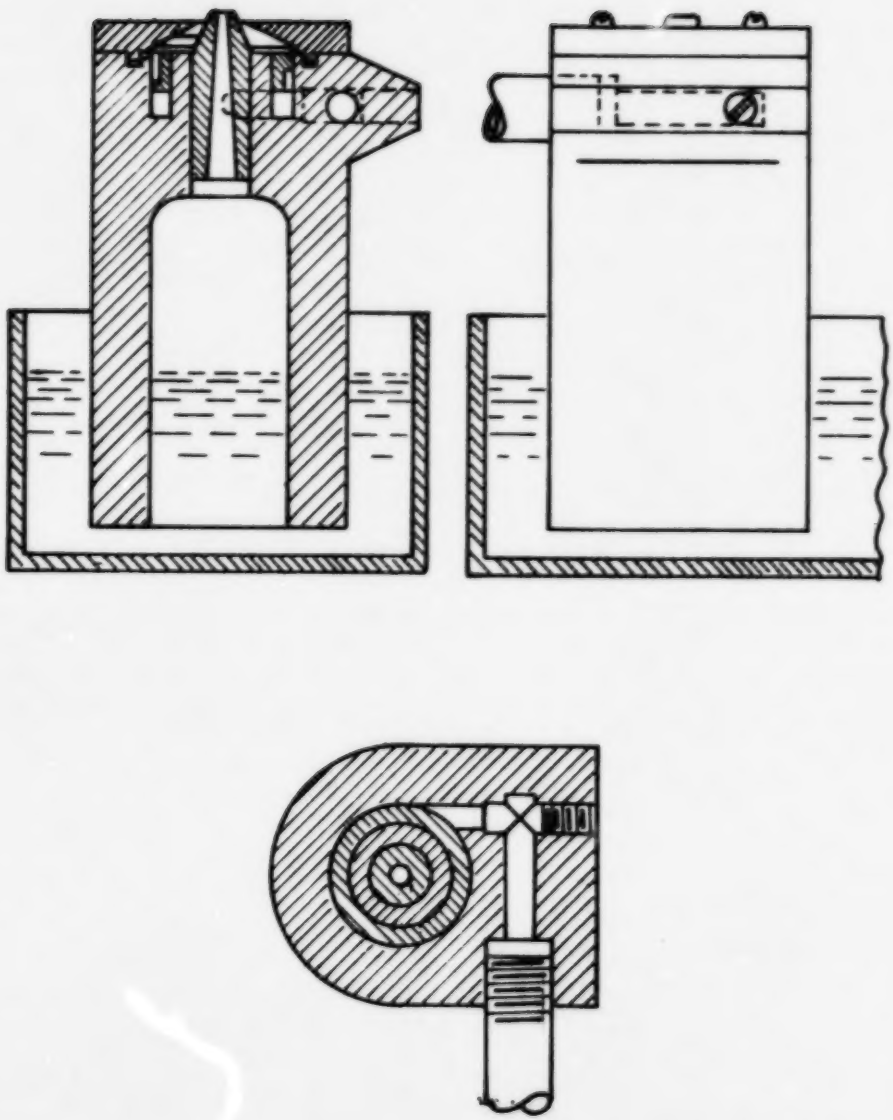


Figure 15. Spray Type Nozzle.

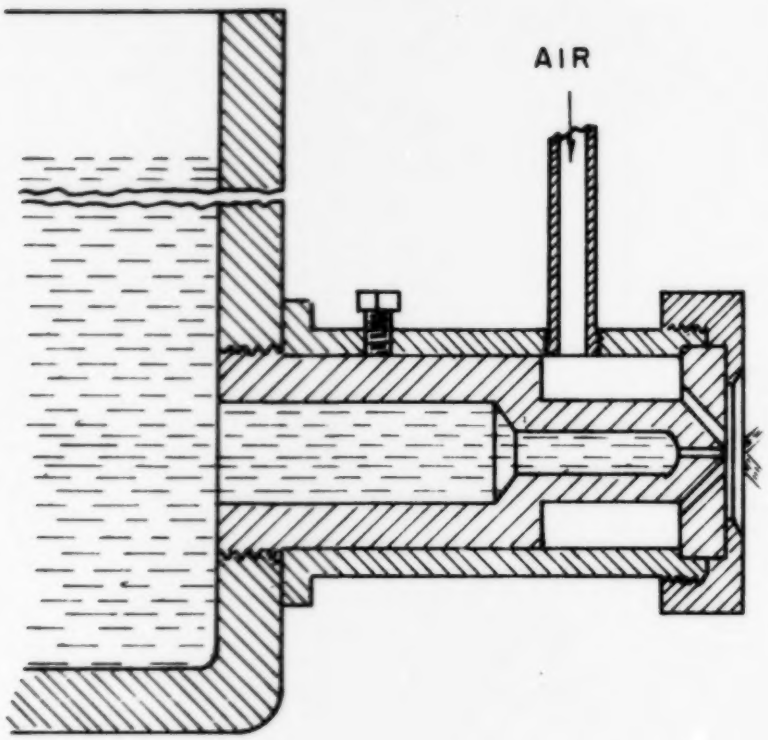


Figure 16. Nozzle Attached to Side of Crucible.

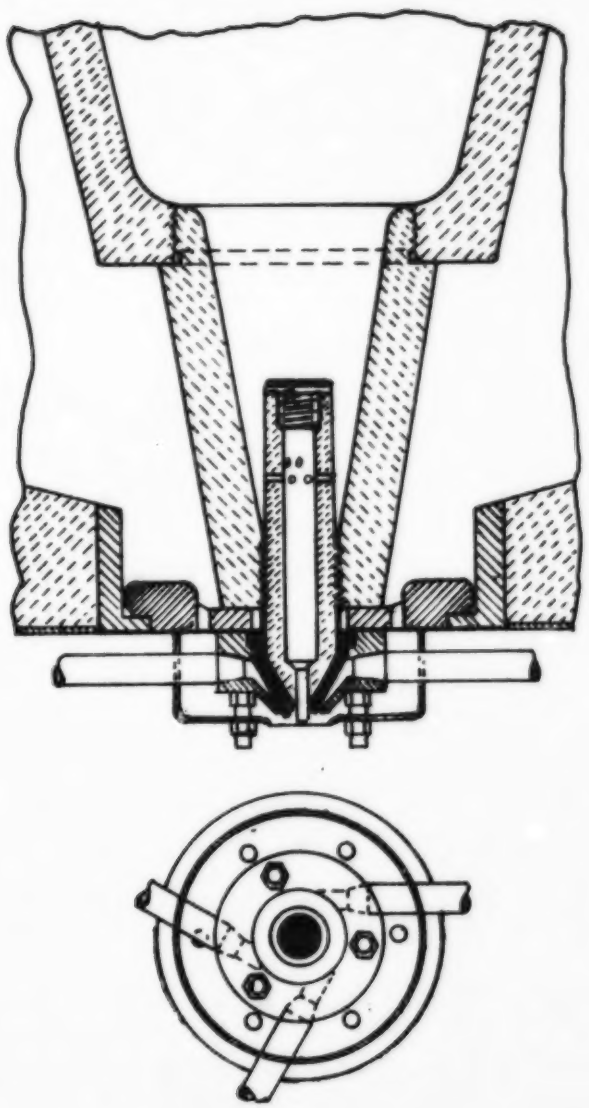


Figure 17. Nozzle Attached to Bottom of Crucible.

of the apparatus that he used.

As previously mentioned, several papers have been published by Russian authors on atomizing non-ferrous and ferrous powders with external annular jets.

2.4. Centrifugal Atomization

2.4.1. Rotating Disc

A method used in industry to produce a controlled dispersion of a variety of liquids by centrifuging them off the edge of a rotating disc is also used to produce metal powders. If molten metal is fed to the centre of a rapidly-revolving disc, friction between the liquid and the disc causes the liquid to attain the same rotational speed as the disc, then centrifugal forces compel the liquid to flow in a thin layer off the edge to be broken up into droplets.

Hinze and Milborn[34], Freidman et al [35], and Walton and Prewett [36] have examined the principles involved in this process and the latter developed the following relationship between drop size and process variables:

$$dw\,(D\rho/T)^{\frac{1}{2}} = \text{constant}$$

where d = drop diameter (cm)

w = angular velocity (radians/sec)

D = diameter of disc (cm)

ρ = liquid metal density (g/cm^3)

T = liquid metal surface tension (dynes/cm)

A more complicated relationship was developed by Freidman et al:

$$D = \text{const } r \left(\frac{T}{\rho n r^2}\right)^{0.6} \left(\frac{\mu}{T}\right)^{0.2} \left(\frac{\rho \sigma L}{T^2}\right)^{0.1}$$

where D = drop diameter (ft)

r = radius of disc (ft)

ρ = density of liquid (lb/cu ft)

n = rate of rotation of disc (rpm)

T = feed rate of liquid to be atomized based on wetted periphery (lb/min/ft)

μ = viscosity of liquid (lb/ft/min.)

σ = surface tension of liquid (pdl/ft).

L - wetted periphery of disc (ft)

These equations show that the size of the droplet and hence the powder particles (~~drops~~) is inversely proportional to the rate of rotation of the disc and that high rates of rotation are required to produce fine powder. Ryley [37] examined the problem of obtaining high disc speeds and designed an apparatus that will attain speeds up to 90,000 rpm. Also, Jones and Burden [38] designed an apparatus to atomize Al-Fe alloys at disc speeds up to 17,188 rpm.

A schematic drawing of the apparatus used by Walton and Prewett is shown in Figure 19. The production of magnesium powder, by the Dow Metal Products Company using this method, is discussed in a paper by Bush [39] in B.P. 746,301 [40], and a patent by the Dow Chemical Company (B.P. 754,180)[41] describes the use of an apparatus for the production of aluminum.

The advantage of producing powders by the centrifugal method is that the particles are of uniform size and the size is controlled by the speed of disc rotation. However, the rate of production is low and this method is suitable only for producing small batches of powder.

2.4.2 Rotating Porous Bucket

Though not concerned with a powder product, a process, described by Severdenko et al [42], produces aluminum granules by pouring molten aluminum into a rotating, preheated, stainless steel bucket with 1 to 2-mm (0.05 to 0.08-in) orifices in the wall. The aluminum is centrifuged through the orifices and drops into a water-filled container. The size of the granules decreases with an increase in the rate of revolution of the bucket (up to 1440 rpm) and melt temperature and with a decrease in orifice diameter.

2.5 Other Types

A recently designed apparatus for atomizing high-melting-point metals has a nozzle similar to the earlier spray nozzles. This apparatus is described by R. Probst[43] and in U.S.P.3,253,783[44]. A schematic drawing of the nozzle in Figure 20 shows that a ceramic

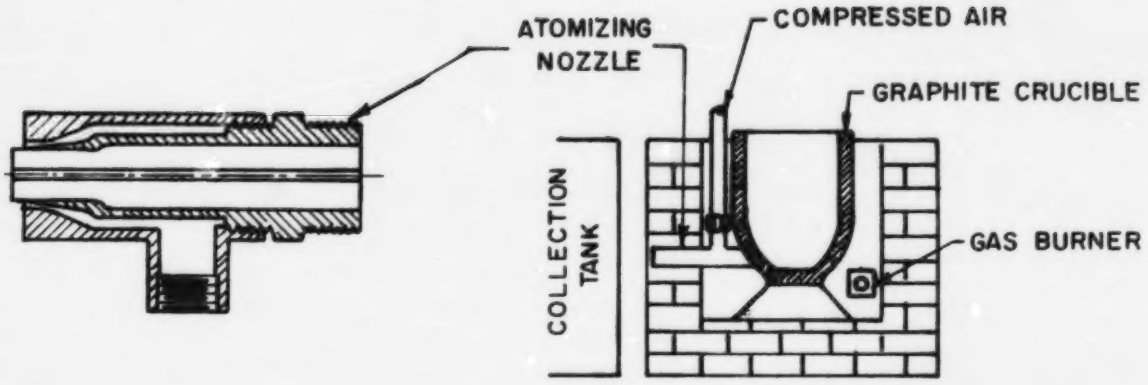


Figure 18. Atomizing Apparatus Used by Thompson.

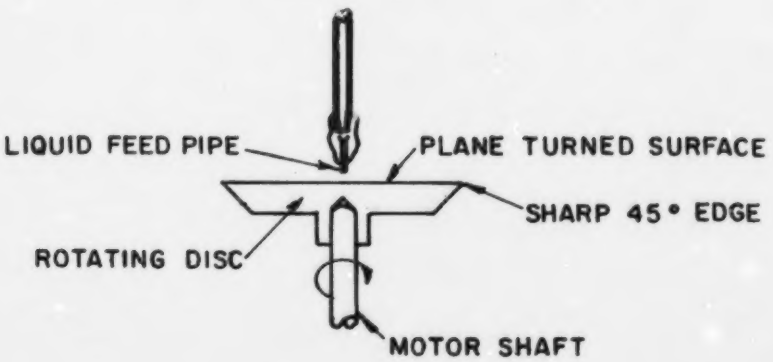


Figure 19. Rotating Disc Atomizing Apparatus.

pouring cup extends through the nozzle to guide the molten metal. The concave shape of the vortex on the pouring cup is similar to a nozzle design by Hall [28]. The object is to spread the metal into a film before it meets the converging jet of liquid or gas at the edge of the vortex. The efficiency of atomization will be increased as the atomizing medium acts on a thin film of molten metal rather than a solid stream. The nozzle has two annular gas chambers arranged to give the emerging gas or liquid a high-speed rotating motion. The apex angle of the jet is 90 degrees and the jet opening is 0.25 to 1 mm (0.01 to 0.05 in.). However, as Probst indicates, it is necessary to preheat the pouring cup to prevent freezing of the metal; erosion of the pouring cup would also be a problem.

In another design by Ullman and Lecznar [45] Figure 21), tangential gas inlets in a nozzle are arranged to create a downward tornado-effect adjacent to the nozzle. It is claimed that this spiral action suspends the atomized particles and allows them to freeze before coming in contact with either the sides or bottom of the chamber. A conical insert directs the molten metal through the annular opening at the perimeter of the orifice, to form a thin film of molten metal on which the gas impinges. Problems with metal freezing on the nozzle and erosion would be expected when atomizing high-melting-point metals.

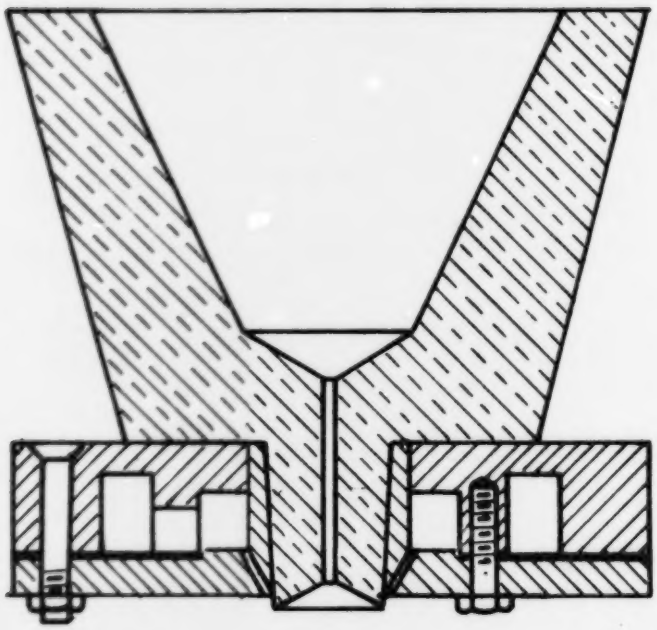


Figure 20. Atomizing Nozzle and Pouring Cup.

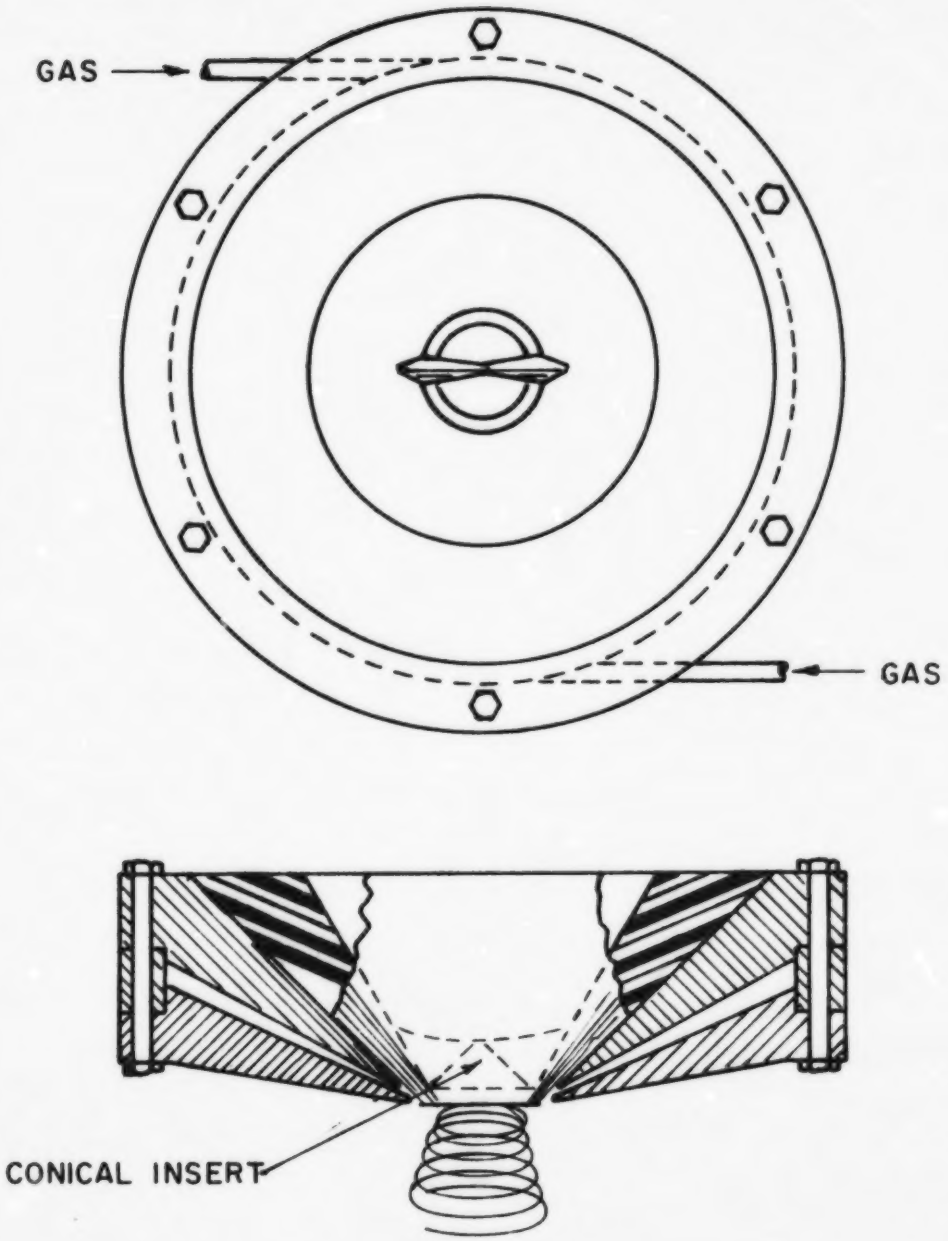


Figure 21. Nozzle for Producing a Tornado-Like Spiral Stream of Gas.

3. SIZES OF POWDERS PRODUCED

3.1. Effect of Parameters

Several investigators have examined the effect of controlling specific process variables on the size of metal powders and have determined that particle size can be influenced by controlling the following:

3.1.1. Surface Tension and Viscosity of Molten Metal

During atomization, fine powder particles are formed more readily when the surface tension and viscosity are lowered. Thompson [33] states that surface tension is the primary factor governing the size of powder particles. Putimtsev [46], on the other hand, contends that, for molten metals solidifying at elevated temperatures, viscosity is the decisive factor. He found that atomizing iron and nickel with air resulted in coarser powder than atomizing with nitrogen, in spite of the fact that oxygen is a surface-active substance and significantly lowers the surface tension of metallic melts. He suggests that the oxygen combines with residual elements such as aluminum and silicon to form viscous oxidation products and thus increases the overall viscosity of the melt. He shows that the presence of aluminum and silicon in air-atomized iron increases the size of the powder particles and states that a protective atomizing atmosphere such as argon or nitrogen will prevent the formation of any viscous oxidation products and, therefore, increase the amount of fine powder.

Superheating the melt and using a hot atomizing medium will lower both the surface tension and viscosity of the melt. Thompson [33] and Sugiyama et al [47] found this to be the case when air-atomizing aluminum, and Small and Bruce [48] produced finer powder of a water-atomized cobalt alloy by increasing the pouring temperature. Putimtsev [46] obtained a two-to-three fold increase in a minus 0.05mm fraction of an iron powder by increasing the temperature of the atomizing gas from 20°C (68°F) to 800°C (1740°F).

There is of course a practical limit to the amount of superheat that can be added to a molten metal before elemental recoveries and refractory material life became seriously affected.

3.1.2 Size of Metal Orifice

With the use of either liquid or gas as the atomizing medium, powder particle size increases directly with the diameter of the metal stream. According to Thompson [33], the energy required to disintegrate the metal stream is a function of the total surface of the powder produced. Hence, an increase in the rate of metal flow to be atomized leads to a coarsening of the powder, other conditions being equal. For this reason, the diameter of metal stream is usually less than 13 mm (0.5 in.).

3.1.3. Pressure of Atomizing Medium

Increasing the pressure of the atomizing liquid or gas increases the available energy which results in an increase in total surface area and, for a constant metal flow, this means

a decrease in particle size. Thompson [33], using air pressures of 0.7 MN/m^2 (100 psi) and less, found a maximum pressure (0.35 MN/m^2, 50 psi), after which there was no further decrease in powder size. He explains that an increase in air pressure (to a spray-type nozzle) can produce a greater induction force on the metal stream, which would mean an increase in quantity of metal available for atomizing. Thus, the two factors, increase in energy input and increase in quantity of metal, would oppose each other and account for a maximum effective pressure. While this conclusion was reached in Thompson's work, other investigators [18,47-49] found only an increase in fine powder with increased gas and water pressures.

The commonly used pressures are: 3.5 to 21 MN/m^2 (500 to 3000 psi) for water and 0.7 to 4 MN/m^2 (100 to 600 psi) for gas.

3.1.4. Apex Angle of Jets

Huseby [50] and Ingram and Durdaller [18] examined the effect of jet apex angle on the size of metal powder. The former found that increasing the included angle between flat jets of water from 10 to 110 degrees produces finer powder and permits the use of lower water pressures to yield the same size powder. At angles greater than 110 degrees some backward deflection of atomized particles occurred.

Ingram and Durdaller obtained an increase in the amount of fine powder by increasing the angle of water jets from 24 to 42 degrees, the angle of annular gas jets from 13 to 17 degrees, and the angle of V-jets of gas from 17 to 28 degrees.

3.1.5. Pressure of Metal Head

Increasing the metal head increases the pressure on the molten metal passing through the orifice and the rate of flow increases. With the atomizing medium at constant pressure, the energy for atomization is constant ; consequently, the increase in metal flow rate causes an increase in powder coarseness.

3.1.6. Nozzle Protrusion

Nozzles similar in design to that used by Thompson [33] and Sugiyama et al [47] have the ability to vary the relative position of the metal and air orifices. With these nozzles there is an optimum protrusion of the inner metal orifice which will give a maximum yield of fine powder.

3.1.7. Shape of Metal Stream

Efforts by Hall [28] and Probst [43] to increase the efficiency of atomization and to produce finer powders by concentrating the energy of the atomizing medium on a thin film of molten metal have been mentioned. In another apparatus developed by Hegmann [51], the molten metal is dispersed in the form of a tubular stream and is atomized by two annular jets of gas; one impinges on the outer circumference of the tubular metal stream, the other on the inner circumference. With this design of nozzle, problems with metal freezing and erosion of the nozzle by the liquid metal would be expected, particularly while atomizing high-melting-temperature metals.

3.2 Mathematical Relationships

Papers by Nichiporenko [52] and Nichiporenko and Naida [53] examine the mathematical relationship between the size of powder and process parameters in the atomization of copper and bronze by a gas jet. They developed the following relationships to determine the conditions for producing copper powder within a required particle size range:

$$\frac{d}{d_e} = 10^{8,485\ Re'} - 1.96$$

$$\frac{d}{d_e} = 10^{8,685\ Re''} - 1.96$$

Re' Reynolds number $\frac{w.'\ de}{V\ air}$

$$w' = \sqrt{\frac{10.\sigma}{d\ \rho}}$$

$$w'' = \sqrt{\frac{14.\sigma}{d\ \rho}}$$

$$d_e = \sqrt{\frac{4\ f}{\pi}}$$

d = metal drop diameter (cm)

σ = surface tension of metal (dynes/cm)

ρ = gas density (gxsec/cm^4)

f = area of a circle whose surface area is equal to the cross sectional area of the annular slot.

V = kinematic viscosity of air (m/sec).

w' = critical gas velocity for commencement of droplet comminution (cm/sec).

w" = second critical gas velocity when droplet comminution occurs instantaneously in the form of an explosion (cm/sec).

Date et al [54] have applied statistical analysis to the production of air-atomized tin powder and claim it is possible to effectively control operating conditions in order to obtain a maximum yield of a powder in a particular particle size.

4. POWDER PARTICLE SHAPE

4.1 Atomizing Medium

When molten metal is atomized by a rapidly moving jet of gas or liquid, the droplets are irregular in shape, but because the surface tension of molten metal is high they have a tendency to become spheroidal before solidifying. Nichiporenko and Naida [55] have investigated the rate at which metal particles (copper, aluminum, and lead), atomized in inert gas, become spherical after atomizing. They found that the time for transformation into a spherical shape is 2.5 to 3.5 orders of magnitude shorter than that needed for cooling to the melting point and 4 to 4.5 orders of magnitude shorter than that needed for complete cooling of the particles. Therefore, inert-gas-atomized metal powders will be spherical if there are no other opposing conditions. The most common obstacle to spheroidization is the formation of a protective oxide film (immediately on atomization) which preserves the initial as-atomized irregular shape. Air-atomized metal powders of aluminum, lead, and zinc come under this heading and are usually irregular

in shape, whereas other air-atomized metal powders such as copper, nickel, and steel are usually spherical.

If water is used as the atomizing medium, the powder particles are cooled more rapidly and the time for the surface tension forces to spheroidize the particles is shorter, therefore there is a stronger tendency for the particles to retain their original irregular shape. With higher water pressures, the distorting force is greater and the larger volume of water causes more rapid quenching.

Experiments by Small and Bruce [48] demonstrated that inert-gas-atomized superalloy powders are spherical regardless of process variables, but the particle shape in water atomized powders can be affected by such variables as melt temperature and water pressure. Also, Jones [56] and Tamura, and Takeda [49] show that water-atomized stainless steel and bronze powders, respectively, are more irregular in shape than air atomized powders.

4.2 Alloying Additions

The shape of atomized metal powders can be controlled, to some extent, by small additions of other elements. It is believed that the alloying elements hinder spheroidization and tend to produce irregular-shaped powders by reducing the surface tension of the melt, increasing the viscosity of the melt, or reacting with oxygen to form stable oxides on the powder particles at the instant of atomization.

F. W. Berk and Co.[57] discovered that additions of Mg, Ca, Li, Ti and Zr to copper will produce irregular-shaped water-atomized powder. According to Nichiporenko and Naida[55], Russian literature maintains that elements such as Mg,Ca,Ti,Mn,Al,and Zn lower the surface tension of molten copper so that the deformed powder particles do not have time to form spheres during cooling. However, their report, and that of Fedorchenko and Nichiporenko [58] state that molten metal (copper, aluminum and lead) forms spheres at a rate fast enough that alloying additions, which lower the surface tension by 30 to 40%, cannot prevent spheroidization. This conclusion is drawn from calculations of spheroidization and cooling rates for inert-gas-atomized powders with uninhibited cooling. Fedorchenko and Nichiporenko suggest that the presence of refractory films surrounding air-atomized particles is one factor preventing spheroidization. In another report [59] Nichiporenko and Naida obtained iregular-shaped air-atomized nickel powder by adding 0.5 wt% Al. In this case, the authors believe that the aluminum forms a refractory oxide, at the instant of atomization, which raises the viscosity of the nickel melt by several orders. This increases the time required for spheroidization to an interval which is longer than that required for cooling and irregular-shaped powder is produced.

Another investigator, Putimtsev[46] states that air-atomized iron, iron-nickel, and iron-cobalt alloy powders containing Al, Ti, and Cr will be irregular in shape due to the formation of refractory oxide films on the powder particles.

It has also been suggested by Jones [60] and Tamura and

Takeda [49] that the size of the temperature gap between the liquidus and solidus has some influence on the particle shape of atomized alloy powders. However, there is a difference of opinion as to this effect. Jones suggest that a large temperature gap will result in a longer time for a particle to freeze and therefore longer for the surface tension forces to form spherical particles. On the other hand, Tamura and Takeda attributes an increase in irregular-shaped copper powder on additions of 10% Sn and 30% Pb to increases in the temperature gap of 190°C (375°F) and 600°C (1110°F), respectively.

4.3 Melt Temperature

The decrease in surface tension of molten metal with increased temperature will favour the production of irregular-shaped atomized powders, but this will be balanced against a reduction in viscosity and a longer time for the particles to form spheres on cooling. Small and Bruce [48] show that, for water atomization, an increase in melt temperature increases the likelihood of spherical powder. However, with gas atomization where the quenching of the particles is less severe, they found that the melt temperature is not important to particle shape. Thompson's [33] work agrees with this. When he air-atomized aluminum, he found no appreciable change in particle shape (ellipsoid) with higher melt temperatures.

4.4 V-Jet Angle

In U.S.P. 2,956,304 [61], Batten and Roberts claim that the shape of metal powder particles can be controlled by rotating

flat liquid V-jets about their longitudinal axis. In the usual position (Figure 5), the flat streams are at 90 degrees to the axis of the metal stream, and the particles tend to be spherical. If the streams are rotated so that the flat surface is parallel to the axis of the metal stream, they are at zero degree, and the particles become irregular. They also state that, at apex angles between 80 and 100 degrees, there is optimum control over the particle shape and size. At apex angles greater than 100 degrees, the particles tend to be spherical and, at angles less than 80 degrees, particles tend to be irregular.

SUMMARY

The influence of some process variables on the size and shape of powder particles atomized by jets of gas or liquid are summarized in Tables 1 and 2. Because the atomizing medium is the dominant factor, particularly in determining particle shape, it is listed with the other factors.

Atomizing processes have made major contributions to the powder metallurgy industry since the beginning of large-scale production of metal powders in the 1940 decade. This review has described many of the developments, especially in the ferrous field. Important modern developments are the inert-atmosphere atomizing processes that have made available an ever increasing range of powders which are being utilized in the automotive and aerospace industries, and a 20% annual growth in this segment of the powder metallurgy field is predicted for several years to come [62].

TABLE 1

Effect of Process Variables on Powder Particle Size

Atomizing Medium	Other Factors	Powder Particle Trend
Inert Gas	-	fine (46)
Air	-	coarse (46)
Air	alloying additions (Al and Si to iron)	coarse (46)
* Gas, water	superheating melt	fine (33,47,48)
Gas	heating atomizing gas	fine (33,46)
Gas, water	size of metal orifice	decrease with size of orifice (33)
Gas, water	pressure of atomizing medium	decrease with increased pressure (18,47-49)
Gas, water	included apex angle of jets	decrease as angle increases (10-110°) (18,50)
Gas	metal head	decrease with reduced metal head (33)
Gas	nozzle protrusion (spray nozzles)	optimum protrusion for fine powder (33,47)

* Gas-air, argon or nitrogen.

TABLE 2

Effect of Process Variables on Powder Particle Shape

Atomizing Medium	Other Factors	Powder Particle Trend
Inert Gas	-	spherical (48,55)
Air (Cu,Ni,Fe)	-	spherical (55)
Air (Al,Pd,Zn)	-	irregular (55)
Water	-	irregular (49,48,56)
Gas	alloying additions to copper (Mg,Ca,Ti,Li, Mn,Al, and Zn)	irregular (55)
Water	alloying additions to copper (Mg,Ca,Li,Ti, and Zr)	irregular (57)
Water	superheating melt	spherical (48)
Water	angle of V-jet to axis $< 90^{o}$	irregular (61)
Water	included V-jet angle $> 100^{o}$	spherical (61)
Water	included V-jet angle $< 80^{o}$	irregular (61)

It appears that one of the few areas open in improving high-temperature and high-strength materials is through powder metallurgy using atomized powders.

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CFD/gm

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